ABF

FINAL REPORT

August 1999

National Aeronautics and
Space Administration

Scientific and Technical
Information Branch

Ground-Based and Small Payloads Research in Space Life Sciences
National Aeronautics and Space Administration

Loads Produced During the Ingression and Egression of the Portable Foot Restraint on the Hubble Space Telescope

Susan Ramsey, NASA
Sudhakar Rajulu, Ph.D., Lockheed Martin

2101 NASA Road 1
Houston, Texas 77058

Anthropometry and Biomechanics Facility (ABF)
NASA/Johnson Space Center

SPACE HUMAN FACTORS

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Abbreviations & Acronyms

ABF	Anthropometry and Biomechanics Facility
EMU	Extravehicular Mobility Unit
EVA	extravehicular activity
FCSD	Flight Crew Support Division
FGS	Fine Guidance Sensors
GSFC	Goddard Space Flight Center
HST	Hubble Space Telescope
MOD	Mission Operations Directorate
NASA	National Aeronautics and Space Administration
NBL	Neutral Buoyancy Laboratory
PFR	Portable Foot Restraint
RSU	Right Sensor Units
STS	Space Transport System

Acknowledgments

The authors wish to acknowledge Erica Miles of the Anthropometry and Biomechanics Facility (ABF), Lockheed-Martin for her software and setup support; Carlos Washington of the ABF, Lockheed-Martin, for his technical and hardware support; Kieth Johnson of the EVA and Crew Systems Operations Branch, Rockwell International for proposing and planning the experiment; the crew of STS-103 for their willing participation in the study; and the Neutral Buoyancy Lab (NBL) divers and personnel for setup and communications support.

1.0 Introduction

1.1 Background

The Hubble Space Telescope (HST) was the first mission of NASA's Great Observatories program. It was deployed from the space shuttle *Discovery* on April 25, 1990 as the primary payload of STS-31. Its is a 2.4 m, f/24 Ritchey-Chretien telescope capable of performing observations in the visible, near-ultraviolet, and near-infrared (1150 A to 1 mm). The HST weighs 12 tons, and collects light with an 8-foot-diameter mirror. The attitude control and maneuvering is performed by four of six gyroscopes, or reaction wheels. In addition, the telescope contains Fine Guidance Sensors (FGS's), which are used to lock onto guide stars to reduce the spacecraft drift and increase the pointing accuracy. Two 2.4 x 12.1 meter solar panels power the two on-board computers and scientific instruments aboard the HST. The solar panels also charge six nickel-hydrogen batteries which provide power to the spacecraft during the approximately 25 minutes in which the HST is within the Earth's shadow.

The HST was designed to last 15 years, with manned service missions approximately every three years. The first service mission, STS-61, was aboard the space shuttle *Endeavor* in 1993, with the main purpose to repair a faulty mirror which was blurring photographs downlinked from the telescope. The second service mission, STS-82, was aboard the space shuttle *Discovery* in February 1997.

In October 1999, the crew of STS-103 will perform the third service mission to the HST aboard the space shuttle *Discovery*. Although a servicing mission was planned for sometime during late 1999 or early 2000, this mission was moved up due to failing gyroscopes aboard the HST. Currently three of the six gyros have failed, and the loss of a fourth would cause a significant reduction in the telescope’s ability to collect science data. The primary purpose of this mission is to replace the Right Sensor Units (RSU's), each of which contain two gyroscopes. In addition, the crew will make improvements on the Fine Guidance Sensors to utilize the most current technology and correct the current optics problems.

In order to perform these tasks on the HST, the crewmembers of STS-103 will be required to use a portable foot restraint (PFR) to anchor themselves to the HST in a zero-gravity environment. The solar arrays currently used on the telescope are second-generation, and therefore susceptible to loads placed on the telescope. There is concern from the crew and their support in Mission Operations Directorate (MOD) as to the damage that could possibly be caused during ingression and egression of the PFR and by transferring loads to the solar arrays. The purpose of this study is to inform the crewmembers of the loads they are imparting on the HST, and train them to decrease these loads to a safer level. By minimizing these loads, the crewmembers will significantly decrease the chance of causing damage to the solar arrays while repairing the HST. A similar test was successfully done with the crew of STS-82, the second HST servicing mission.

1.2 Purposes of the Study

Specifically, the purposes of this study were to:

1 Determine the level of forces and moments applied to the outside of the Hubble Space Telescope (HST) during nominal ingress and egress of the Portable Foot Restraint (PFR) by each of the crewmembers who are selected to perform extravehicular activity (EVA) work on the HST during STS-103.
2 Determine the level of forces and moments applied to the outside of the HST as each crewmember attempted to decrease their ingress and egress loads.
3 Evaluate the spike loading and sustained loading for applied forces and moments for each crewmember during each ingress and egress trial.

2.0 General Methodology

2.1 Subjects

Four astronaut subjects, who will be the crewmembers qualified to perform an EVA on the STS-103 HST repair mission, participated in this study. They consisted of Mike Foale, John Grunsfeld, Claude Nicollier, and Steve Smith.

2.2 Apparatus

The primary testing apparatus was a force plate setup built in the Anthropometry and Biomechanics Facility (ABF). This apparatus consisted of a small waterproof AMTI load cell mounted on two L-shaped iron angles. A PFR socket connector was used to connect this apparatus to the PFR socket on the HST. On top of the load cell, an adapted PFR socket was placed for the actual PFR testing unit to be attached. See Figure 1 for the mounted force plate setup. The entire force plate apparatus was attached to a full-size HST mockup submerged in the Neutral Buoyancy Laboratory (NBL). A PFR was then attached to the apparatus for the crewmembers to use during ingress and egress.

The load cell amplifier was connected to a portable data acquisition computer. A LabVIEW-based data acquisition program was used to collect data for this experiment. Data points for force and moment were collected at a frequency 100 Hz, or at a 0.01 time interval.

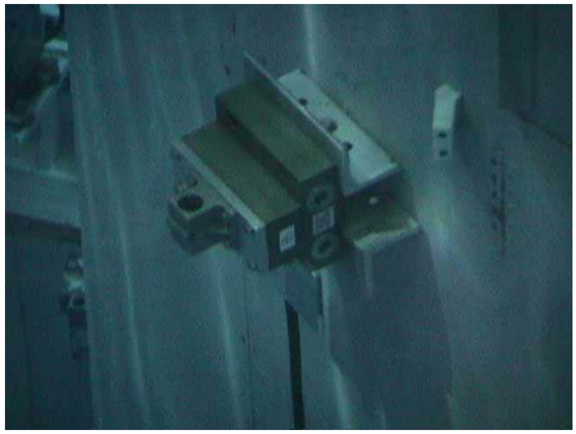


Figure 1: Load Cell Apparatus Setup (attached to the HST Mockup in the NBL)

2.3 Experimental Design

All of the testing took place at the Neutral Buoyancy Lab (NBL) at the Sonny Carter Training Facility at NASA – Johnson Space Center. This training facility is the most accurate simulation of a zero-gravity outer space environment available for crew training.
The EMU-suited crewmembers were submerged in the NBL and appropriately weighted to achieve neutral buoyancy.

The main objective of this study was to determine the loads applied to the HST during ingress and egress of the PFR by the crewmembers. Each crewmember performed a nominal ingress and egress trial, and then attempted to minimize their input loads on further trials. The crewmembers were given real-time verbal feedback of their input loads after each trial. There was no specific range of forces and moments that the crewmembers were attempting to reach. The goal of the experiment was to provide each crewmember with his own load feedback whereby he could decrease the input load on future trials.

2.4 Experimental Procedure

This experiment was done in conjunction with other training efforts of the STS-103 crewmembers at the NBL. Prior to the actual experiment, one of the NBL divers submerged the load cell apparatus and connected it to the HST mockup on the eleventh PFR socket. The data acquisition computer connected to the load cell amplifier was zeroed at this point. The diver then connected the PFR to the adapted socket on the load cell apparatus, and the computer was zeroed again. This completed the setup for the experiment.

Prior to beginning the experiment, each crewmember was given a verbal briefing of how the experiment would take place, and the end goal of the project. Once the crewmember and the test director signaled, the data acquisition software was activated on the computer, and the crewmember was instructed to begin nominal ingress. See Figure 2 for PFR ingress. After successful data acquisition, real-time feedback was given to the crewmember about his ingress forces for that trial. The data acquisition software was then reactivated, and the crewmember was instructed to begin nominal egress. Real-time feedback was then given about egress values. The testing was repeated with the crewmembers altering different aspects of their ingress and egress procedure each time. A minimum of one nominal trial and three test trials of both ingress and egress were completed by each crewmember. Additional trials were performed at the crewmember's request.

Data was also collected at a variety of times while the crewmember was in the PFR. Although this data was not pertinent to this test, it is beneficial to put the maximum ingress and egress values into perspective. See Appendix B for these values.

This procedure was repeated for each of the four crewmembers participating in this study.

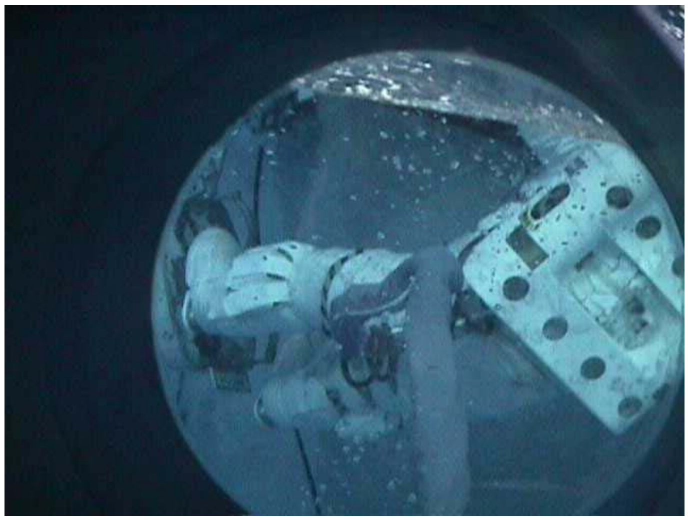


Figure 2: Crewmember ingressing the PFR on the HST Mockup

2.5 Data Treatment

The raw data collected from the data acquisition computer was in columnar text file format. These columns contained time, force, and moment data, respectively. A single file was created for each individual trial.

For the purposes of analysis, each of the files was opened into a Microsoft Excel spreadsheet format and analyzed using spreadsheet tools.

2.6 Analysis

The data from each of these trials was analyzed for sustained and spike forces and moments. Spike loads and moments capture the sudden jerk motions transmitted to the HST. Sustained loads and moments capture the summed average of all nominal and jerk forces and moments exerted during ingress and egress. The sustained data will be used to determine if the overall load was reduced due to training. The spike data will determine whether crewmembers were able to prevent any unnecessary impulses to the HST during ingress and egress.

The sustained force was defined as the average force during the given trial in a given direction. Sustained force values were calculated based on absolute-value figures for each direction, according to Cartesian planes. Sustained resultant forces for each time interval were also calculated. The orientation of the Cartesian planes according to the AMTI load cell and its placement on the HST mockup are presented in Figure 3. Similar analysis was done to calculate a sustained resultant moment.

The spike force was defined as the maximum force exerted during the given trial in a given direction. A spike force in both the positive and negative direction was calculated for each of the Cartesian planes. Resultant forces for each time interval were also calculated, and the resultant spike force was determined. Similar analysis was done to calculate a resultant spike moment.

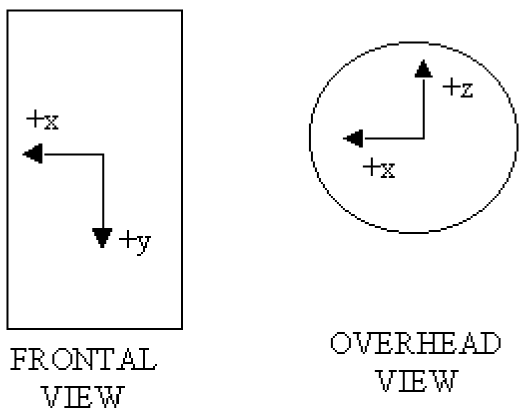
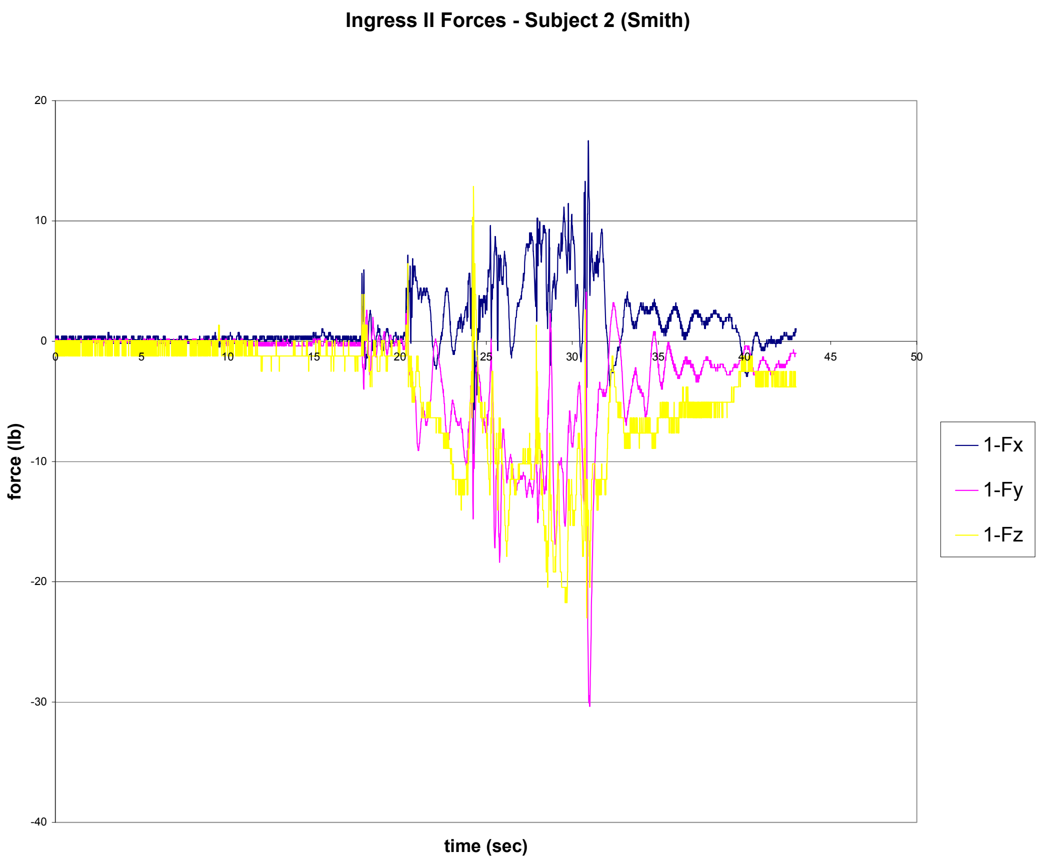


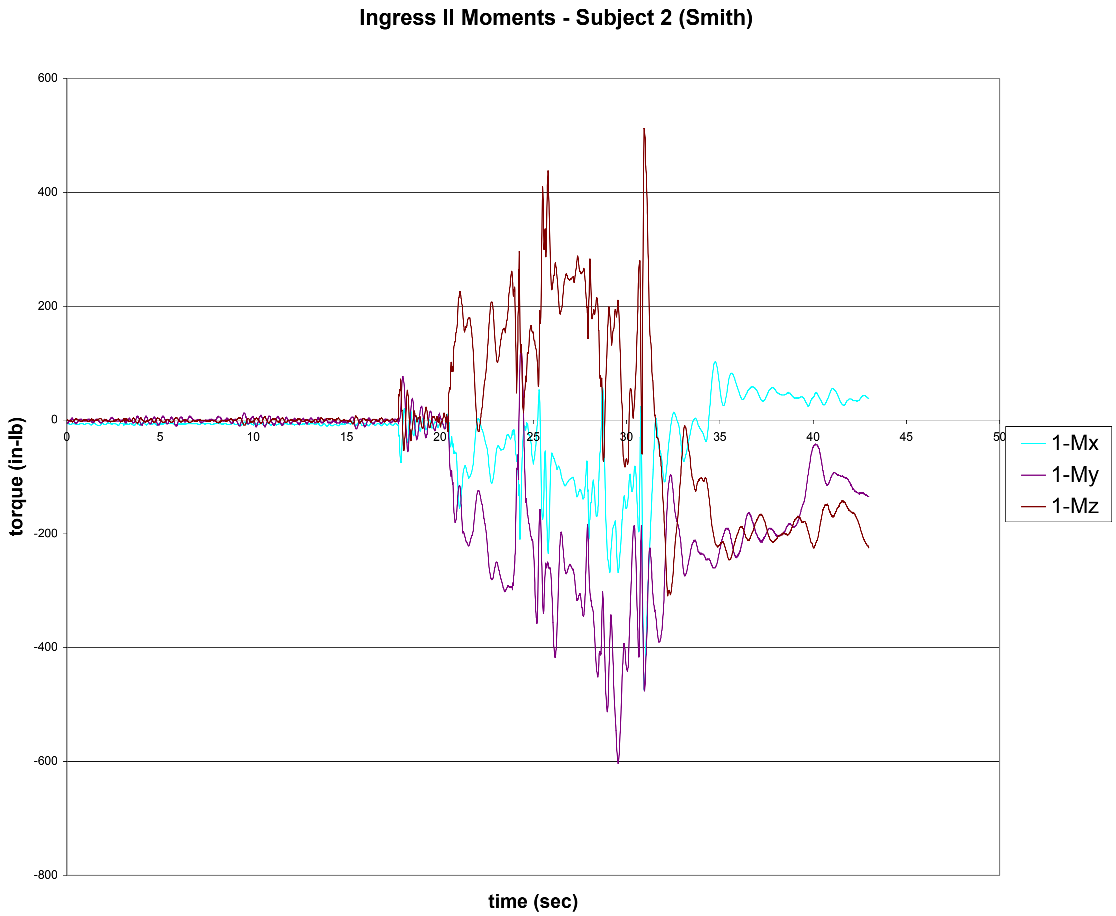
Figure 3: Orientation of Cartesian Planes According to the AMTI Load Cell and Its Placement on the Hubble Space Telescope

In addition, both force and moment graphs were made of each trial to compare input loads versus time. An example of a force versus time graph is given below:



Graph 1: Force versus Time Graph - Ingress (Example)

Similar graphs were also generated for torque versus time, or moment data.



Graph 2: Torque versus Time Graph - Ingress (Example)

3.0 Results

3.1 Sustained Force and Moment Analysis

The sustained force and moment analysis was performed for every trial completed by the four test subjects. A percentage comparison was done between the nominal and subsequent reduced-load trials for the forces and moments in each direction. See Appendix A for this comparison.

A comparison between the nominal load and the most efficient, or lowest reduced-load, is given in the charts below. The nominal sustained resultant force (Nom. Rf) is the average resultant force measured during the crewmembers' first attempt at ingress or egress. The lowest, or most efficient, reduced-load (Min Rf) the smallest sustained resultant force measured during one of the trials. These two values are compared for ingress and egress below. A similar comparison is also made between the nominal sustained resultant moment (Nom. Rm) and the lowest reduced-load (Min Rm) moment.

Table 1: Percent Difference Comparison Between Sustained Nominal and Most Efficient (Lowest Reduced-Load) Forces and Moments – Ingress

	Reduced-Load Force			Reduced-Load Moment		
Subject	**Nominal**	**Minimum**	**Diff.**	**Nominal**	**Minimum**	**Diff.**
1	15.1	12.0	20%	391.3	258.1	34%
2	7.9	8.4	-7%	231.8	201.6	13%
3	20.6	12.8	38%	547.9	354.9	35%
4	9.7	6.6	33%	242.9	180.4	26%
AVG.	**13.3**	**10.0**	**21%**	**353.5**	**248.8**	**27%**

Table 2: Percent Difference Comparison Between Sustained Nominal and Most Efficient (Lowest Reduced-Load) Forces and Moments - Egress

	Reduced-Load Force			Reduced-Load Moment		
Subject	**Nominal**	**Minimum**	**Diff.**	**Nominal**	**Minimum**	**Diff.**
1	8.7	6.5	26%	184.7	161.6	12%
2	7.7	11.1	-45%	216.7	313.5	-45%
3	15.2	15.5	-2%	279.3	388.9	-39%
4	10.5	8.6	18%	213.0	167.5	21%
AVG.	**10.5**	**10.4**	**-1%**	**223.4**	**257.9**	**-12%**

From these tables, it can be seen that the nominal loads during ingress were significantly higher than those during nominal egress. As a result of this training exercise, however, crewmembers were able to decrease their sustained resultant force and moment much more significantly during ingress than egress. During ingress, they were able to achieve a

21% decrease in force, and a 27% decrease in moment. During egress, however, two of the subjects were not able to decrease their forces or moments in any of their reduced-load trials from their nominal trial. This greatly affected the average percent difference for the four subjects. Although Subject 1 and Subject 4 were able to decrease their egress sustained resultant force through this training, the overall difference between the nominal and reduced-load force trials for egress was nearly zero. Similar patterns were seen for moment data, with the average reduced-load moment data actually greater than the average nominal moment data.

3.2 Spike Force and Moment Analysis

Spike force and moment analysis was also performed for every trial completed by the four test subjects. A percentage comparison was done between the nominal and reduced-load trials for the forces and moments in each direction. See Appendix A for this comparison.

A comparison between the nominal load and the most efficient, or lowest reduced-load, is given in the charts below. The nominal spike resultant force (Nom. Rf) is the maximum resultant force measured during the crewmembers' first attempt at ingress or egress. The lowest, or most efficient, reduced-load (Min Rf) the smallest maximum resultant force measured during one of the trials. For the Min Rf, the maximum resultant was calculated for each of the ingress and egress trials. The trial with the smallest maximum value was used for the Min Rf. The Nom Rf and Min Rf values are compared for ingress and egress below. A similar comparison is also made between the nominal sustained resultant moment (Nom. Rm) and the lowest reduced-load (Min Rm) moment.

Table 3: Percent Difference Comparison Between Spike Nominal and Most Efficient (Lowest Reduced-Load) Forces and Moments – Ingress

	Reduced-Load Force			Reduced-Load Moment		
Subject	**Nominal**	**Minimum**	**Diff.**	**Nominal**	**Minimum**	**Diff.**
1	68.0	38.9	43%	1580.3	928.6	41%
2	42.1	31.0	26%	840.9	544.3	35%
3	92.2	37.8	59%	2177.0	1170.6	46%
4	68.3	30.7	55%	1056.9	546.0	48%
AVG.	**67.6**	**34.6**	**46%**	**1413.8**	**797.4**	**43%**

Table 4: Percent Difference Comparison Between Spike Nominal and Most Efficient (Lowest Reduced-Load) Forces and Moments - Egress

	Reduced-Load Force			Reduced-Load Moment		
Subject	**Nominal**	**Minimum**	**Diff.**	**Nominal**	**Minimum**	**Diff.**
1	28.3	16.6	41%	611.8	334.1	45%
2	25.2	19.7	22%	756.7	590.6	22%
3	67.5	48.8	28%	1405.4	1288.8	8%
4	26.4	35.0	-33%	659.1	749.2	-14%
AVG.	**36.8**	**30.0**	**15%**	**858.3**	**740.6**	**15%**

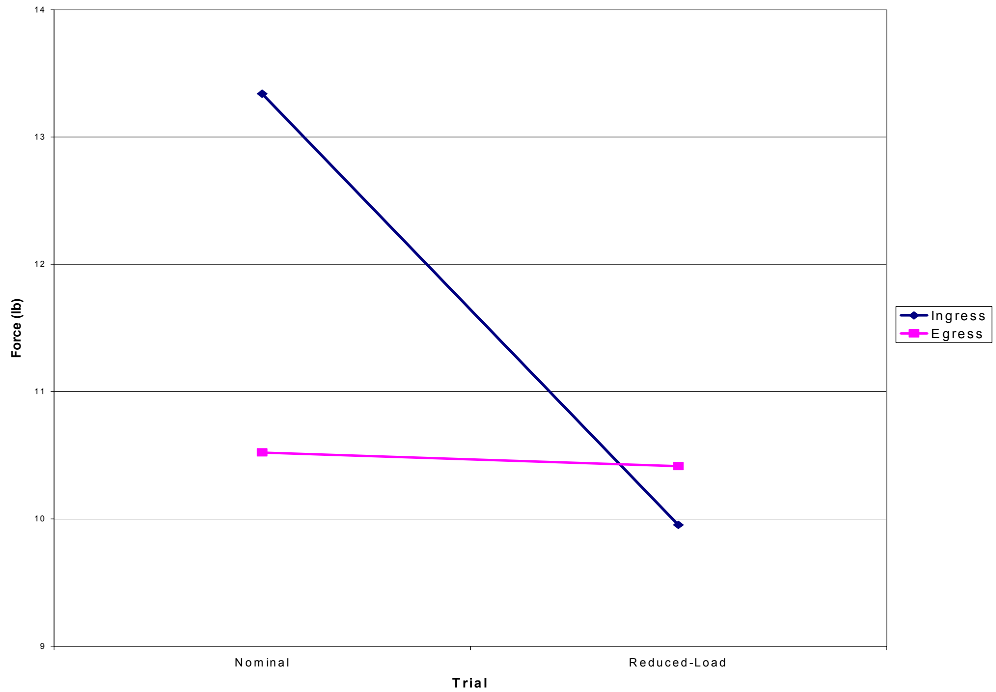
Similar to the sustained forces and moments, it can be seen that the nominal ingress loads were significantly greater than the nominal egress loads. However, this study provided training that enabled the crewmembers to decrease their spike resultant force and moment much more significantly during ingress than egress. During ingress, they were able to achieve a 46% decrease in force, and a 43% decrease in moment. Different from the sustained load analysis, most of the subjects were able to decrease their resultant input forces and moments through reduced-load trials during egress. Subject 4, however, continuously had higher resultant force and moment data for each of the reduced-load trials after his nominal trial during egress. The overall average percent difference for both spike resultant forces and moments was 15%.

Although the training was not able to substantially affect the crewmembers' ability to decrease input loads during egress, the overall forces and moments applied to the HST during egress were still lower than those applied during ingress.

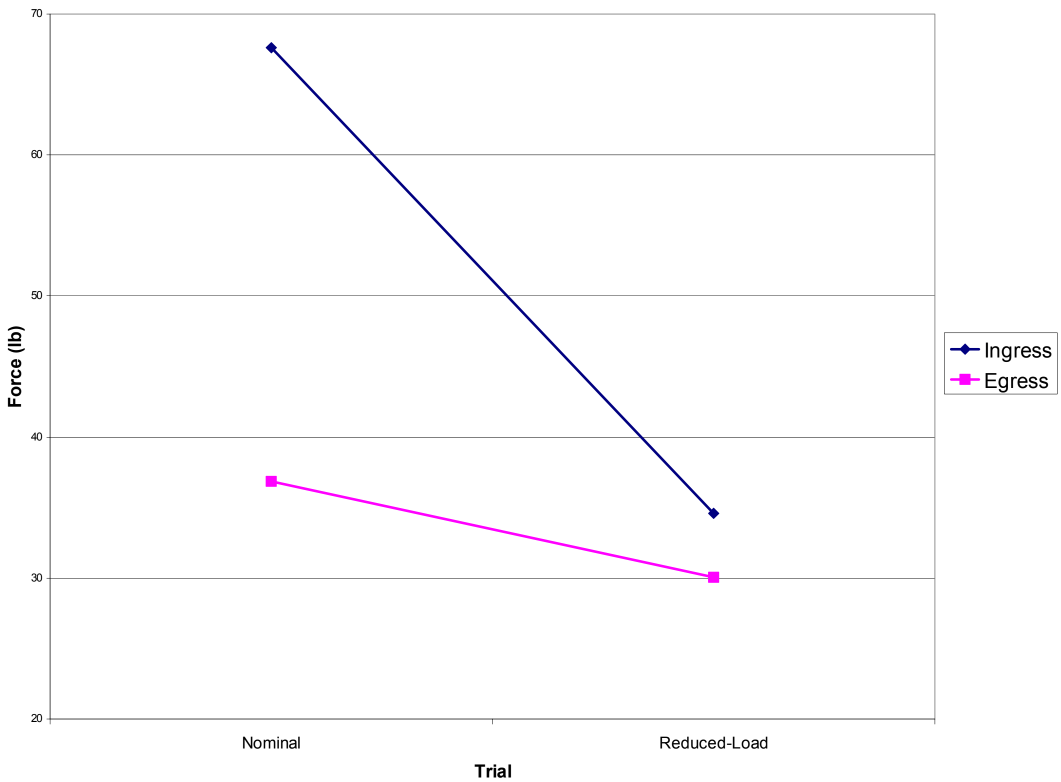
4.0 Discussion

The purpose of this study was to provide real-time training feedback for the crewmembers of STS-103 in an effort to decrease the loads applied to the HST during an EVA. As shown in both the sustained and spike data, the ingress loads were substantially higher than the egress loads during the nominal trial; therefore, it was more important during this exercise for the crewmembers to focus on decreasing ingress loads. This training was highly successful in providing information to the crewmembers that allowed them to adjust their ingress procedure and decrease their input loads. Surprisingly, the training was not nearly as effective during egress, as there was not a significant decrease in the either the forces or moments created during these trials. Despite the varying effectiveness of the training, however, the end spike forces and moments applied during egress remained lower than the end spike forces and moments applied during ingress. This was due, in part, to the constant trend of egress loads to be significantly lower than ingress loads, particularly during the nominal trial.

Graphs are given below to show the decrease in force values between the nominal and reduced-load trials for ingress and egress. Graph 3 shows the values for sustained force, and Graph 4 shows the values for spike force. As displayed visually on these graphs, the decrease in force for ingress is much more significant than for egress, but the final values for both ingress and egress are similar.



Graph 3: Sustained Forces: Nominal versus Reduced Loads



Graph 4: Spike Forces: Nominal versus Reduced Load

5.0 Conclusion and Application

During their extravehicular activities, the crew of STS-103 will be required to ingress and egress the portable foot restraint on the Hubble Space Telescope. Through the verbal real-time feedback given during this test, the crew can now feel more comfortable and familiar with the loads they are applying to the HST during different body positions and scenarios. The analysis of the data gathered during this testing proves that the subjects were able to significantly reduce the loads that they were originally applying to the HST. Overall the training was substantially more successful for decreasing ingress loads, but the egress loads were relatively low even during the nominal trials. The end result ingress and egress loads for each of the subjects were very similar to one another.

The Mission Operations Directorate (MOD) counterparts working with the crew of STS-103 felt that these reduced-loads achieved by the crewmembers were sufficient for the safe completion of each EVA during this HST repair mission. The data has been transferred to another analysis group at Goddard Space Flight Center (GSFC) for further analysis of the exact loads being put on the solar arrays of the HST during the crewmembers' ingress and egress.

Overall, this study was successful in providing real-time training feedback to the crewmembers, and well as producing data which showed the crewmembers' ability to adjust their input loads during ingress and egress of a PFR. This data can be used in future missions by mission planners concerned about the input loads to an object during EVA.

Appendix A: Comparison of Nominal versus Reduced-Load Trials

Table 5: Overall Sustained Force Values - Ingress
This chart displays the directional and resultant sustained force (lb) values for each of the four test subjects during each of their trials ingressing the PFR.

Subject	Trial	Fx	Fy	Fz	R	Fx Diff	Fy Diff	Fz Diff	R Diff
1	Nominal	7.7	7.7	7.4	13.14	0%	0%	0%	0%
	Ingress II	6.2	7.1	7.4	12.00	19%	8%	-1%	9%
	Ingress III	5.1	6.8	6.9	10.98	34%	12%	6%	16%
	Ingress IV	6.0	7.5	7.3	12.10	21%	3%	0%	8%
2	Nominal	3.5	4.2	4.5	7.06	0%	0%	0%	0%
	Ingress II	2.9	4.9	7.0	9.03	19%	-17%	-57%	-28%
	Ingress III	3.4	4.4	5.3	7.66	3%	-4%	-18%	-9%
	Ingress IV	4.9	6.9	7.0	10.98	-39%	-65%	-57%	-56%
3	Nominal	7.9	10.8	12.9	18.58	0%	0%	0%	0%
	Ingress II	5.2	8.2	9.9	13.88	34%	24%	23%	25%
	Ingress III	4.7	6.1	8.9	11.77	41%	43%	31%	37%
	Ingress IV	5.5	7.3	10.8	14.16	30%	33%	16%	24%
	Ingress V	5.0	6.1	11.9	14.30	36%	43%	8%	23%
4	Nominal	4.0	5.3	5.5	8.64	0%	0%	0%	0%
	Ingress II	4.9	5.8	5.2	9.22	-24%	-9%	6%	-7%
	Ingress III	3.3	3.1	3.6	5.73	18%	42%	35%	34%
	Ingress IV	4.1	4.6	3.8	7.28	-4%	14%	31%	16%

Table 6: Overall Sustained Force Values- Egress

This chart displays the directional and resultant sustained force (lb) values for each of the four test subjects during each of their trials egressing the PFR.

Subject	Trial	Fx	Fy	Fz	R	Fx Diff	Fy Diff	Fz Diff	R Diff
1	Nominal	4.1	5.0	4.2	7.76	0%	0%	0%	0%
	Egress II	4.0	4.4	2.9	6.64	3%	12%	31%	14%
	Egress III	3.0	3.3	3.6	5.72	28%	34%	14%	26%
	Egress IV	3.4	4.6	3.8	6.85	19%	8%	11%	12%
2	Nominal	4.1	4.3	3.2	6.76	0%	0%	0%	0%
	Egress II	5.9	9.8	7.5	13.65	-44%	-129%	-131%	-102%
	Egress III	3.3	7.4	6.5	10.42	21%	-74%	-102%	-54%
	Egress IV	4.8	8.9	5.8	11.68	-16%	-109%	-79%	-73%
3	Nominal	8.4	8.6	5.7	13.24	0%	0%	0%	0%
	Egress II	5.6	8.2	10.6	14.54	33%	4%	-88%	-10%
	Egress III	7.2	11.9	13.5	19.38	14%	-39%	-139%	-46%
	Egress IV	4.9	11.7	13.4	18.44	41%	-36%	-137%	-39%
	Egress V	8.1	11.9	15.1	20.84	3%	-38%	-167%	-57%
4	Nominal	4.4	5.3	6.2	9.25	0%	0%	0%	0%
	Egress II	5.7	8.6	5.4	11.63	-28%	-63%	13%	-26%
	Egress III	6.2	6.5	5.8	10.69	-41%	-22%	6%	-16%
	Egress IV	4.1	5.0	4.2	7.73	6%	5%	32%	16%

Table 7: Overall Sustained Moment Values - Ingress

This chart displays the directional and resultant sustained moment (in-lb) values for each of the four test subjects during each of their trials ingressing the PFR.

Subject	Trial	Mx	My	Mz	R	Mx Diff	My Diff	Mz Diff	R Diff
1	Nominal	164.4	219.5	199.0	338.88	0%	0%	0%	0%
	Ingress II	149.9	215.6	131.9	293.89	9%	2%	34%	13%
	Ingress III	137.2	173.3	129.0	255.93	17%	21%	35%	24%
	Ingress IV	139.1	155.2	116.7	238.91	15%	29%	41%	30%
2	Nominal	60.9	144.2	145.2	213.50	0%	0%	0%	0%
	Ingress II	67.4	205.2	154.8	265.77	-11%	-42%	-7%	-24%
	Ingress III	54.8	133.0	113.8	183.41	10%	8%	22%	14%
	Ingress IV	95.1	199.3	152.1	268.16	-56%	-38%	-5%	-26%
3	Nominal	306.9	328.4	234.3	506.87	0%	0%	0%	0%
	Ingress II	218.9	265.3	146.6	373.90	29%	19%	37%	26%
	Ingress III	199.8	251.8	101.7	337.12	35%	23%	57%	33%
	Ingress IV	241.3	292.5	143.2	405.35	21%	11%	39%	20%
	Ingress V	129.5	412.9	169.2	464.59	58%	-26%	28%	8%
4	Nominal	146.7	102.1	120.8	215.70	0%	0%	0%	0%
	Ingress II	121.2	112.3	145.5	220.19	17%	-10%	-20%	-2%
	Ingress III	102.7	78.9	90.4	158.00	30%	23%	25%	27%
	Ingress IV	112.8	105.5	137.9	207.00	23%	-3%	-14%	4%

Table 8: Overall Sustained Moment Values - Egress

This chart displays the directional and resultant sustained moment (in-lb) values for each of the four test subjects during each of their trials egressing the PFR.

Subject	Trial	Mx	My	Mz	R	Mx Diff	My Diff	Mz Diff	R Diff
1	Nominal	70.0	94.9	115.5	165.10	0%	0%	0%	0%
	Egress II	56.0	98.5	81.8	139.73	20%	-4%	29%	15%
	Egress III	60.1	134.8	74.1	165.15	14%	-42%	36%	0%
	Egress IV	96.3	107.9	144.5	204.43	-38%	-14%	-25%	-24%
2	Nominal	100.6	113.1	134.0	202.19	0%	0%	0%	0%
	Egress II	168.8	217.3	208.3	345.07	-68%	-92%	-55%	-71%
	Egress III	61.5	205.9	191.5	287.89	39%	-82%	-43%	-42%
	Egress IV	74.0	183.0	291.2	351.77	27%	-62%	-117%	-74%
3	Nominal	138.3	145.0	159.7	256.24	0%	0%	0%	0%
	Egress II	181.5	231.6	222.0	368.63	-31%	-60%	-39%	-44%
	Egress III	237.3	335.8	291.3	503.98	-72%	-132%	-82%	-97%
	Egress IV	246.8	334.6	304.6	515.39	-78%	-131%	-91%	-101%
	Egress V	289.1	361.1	264.3	532.77	-109%	-149%	-66%	-108%
4	Nominal	124.0	121.9	63.5	185.10	0%	0%	0%	0%
	Egress II	207.3	160.9	189.2	323.50	-67%	-32%	-198%	-75%
	Egress III	174.9	312.2	215.0	417.49	-41%	-156%	-238%	-126%
	Egress IV	98.6	81.5	78.4	150.05	20%	33%	-23%	19%

Table 9: Overall Spike Force Values – Ingress

This chart displays the directional and resultant spike force (lb) values for each of the four test subjects during each of their trials ingressing the PFR.

Subject	Trial	Fx	Fy	Fz	R	Fx Diff	Fy Diff	Fz Diff	R Diff
1	Nominal	37.4	42.7	45.1	72.45	0%	0%	0%	0%
	Ingress II	34.3	31.3	42.1	62.67	8%	27%	7%	13%
	Ingress III	22.7	31.3	29.3	48.49	39%	27%	35%	33%
	Ingress IV	30.0	37.0	28.0	55.25	20%	13%	38%	24%
2	Nominal	25.3	20.8	39.8	51.52	0%	0%	0%	0%
	Ingress II	16.7	30.4	23.0	41.58	34%	-46%	42%	19%
	Ingress III	19.8	16.0	24.3	35.17	22%	23%	39%	32%
	Ingress IV	19.7	31.3	21.7	42.88	22%	-50%	45%	17%
3	Nominal	54.5	89.3	66.2	123.79	0%	0%	0%	0%
	Ingress II	33.4	31.7	35.5	58.13	39%	64%	46%	53%
	Ingress III	30.6	29.6	44.4	61.57	44%	67%	33%	50%
	Ingress IV	41.9	23.9	43.2	64.78	23%	73%	35%	48%
	Ingress V	24.8	26.1	30.3	47.07	55%	71%	54%	62%
4	Nominal	24.1	41.9	66.4	82.14	0%	0%	0%	0%
	Ingress II	25.2	21.6	52.3	61.92	-4%	48%	21%	25%
	Ingress III	20.9	15.9	29.7	39.65	13%	62%	55%	52%
	Ingress IV	15.7	28.1	29.2	43.49	35%	33%	56%	47%

Table 10: Overall Spike Force Values - Egress

This chart displays the directional and resultant spike force (lb) values for each of the four test subjects during each of their trials egressing the PFR.

Subject	Trial	Fx	Fy	Fz	R	Fx Diff	Fy Diff	Fz Diff	R Diff
1	Nominal	19.6	25.6	15.6	35.83	0%	0%	0%	0%
	Egress II	14.1	15.4	9.2	22.82	28%	40%	41%	36%
	Egress III	17.5	18.7	18.1	31.38	11%	27%	-16%	12%
	Egress IV	17.1	18.4	11.3	27.60	13%	28%	27%	23%
2	Nominal	12.7	22.6	16.6	30.76	0%	0%	0%	0%
	Egress II	27.4	28.3	24.3	46.28	-116%	-25%	-46%	-50%
	Egress III	9.9	15.4	14.0	23.07	22%	32%	15%	25%
	Egress IV	15.4	25.0	20.5	35.78	-22%	-11%	-23%	-16%
3	Nominal	54.5	57.8	26.5	83.75	0%	0%	0%	0%
	Egress II	27.6	32.6	34.2	54.71	49%	44%	-29%	35%
	Egress III	37.4	38.6	43.2	68.92	31%	33%	-63%	18%
	Egress IV	20.8	35.0	29.1	50.05	62%	39%	-10%	40%
	Egress V	25.1	45.5	34.2	62.22	54%	21%	-29%	26%
4	Nominal	18.6	24.5	22.0	37.88	0%	0%	0%	0%
	Egress II	24.4	41.0	40.0	62.28	-31%	-67%	-81%	-64%
	Egress III	34.2	35.0	39.5	62.91	-84%	-43%	-79%	-66%
	Egress IV	16.0	30.2	16.9	38.16	14%	-23%	23%	-1%

Table 11: Overall Spike Moment Values – Ingress

This chart displays the directional and resultant spike moment (in-lb) values for each of the four test subjects during each of their trials ingressing the PFR.

Subject	Trial	Mx	My	Mz	R	Mx Diff	My Diff	Mz Diff	R Diff
1	Nominal	1174.3	1293.3	787.2	1916.00	0%	0%	0%	0%
	Ingress II	635.1	916.6	541.4	1239.57	46%	29%	31%	35%
	Ingress III	517.0	829.4	477.1	1087.57	56%	36%	39%	43%
	Ingress IV	687.1	525.9	696.5	1110.78	41%	59%	12%	42%
2	Nominal	366.6	687.1	611.6	990.26	0%	0%	0%	0%
	Ingress II	475.4	603.3	512.6	923.48	-30%	12%	16%	7%
	Ingress III	223.2	394.1	541.5	705.88	39%	43%	11%	29%
	Ingress IV	433.7	516.1	562.1	877.79	-18%	25%	8%	11%
3	Nominal	1319.8	1600.9	1602.3	2621.51	0%	0%	0%	0%
	Ingress II	951.8	788.3	695.0	1417.92	28%	51%	57%	46%
	Ingress III	830.4	915.6	523.5	1342.33	37%	43%	67%	49%
	Ingress IV	614.0	1079.5	839.1	1498.80	53%	33%	48%	43%
	Ingress V	657.6	1019.7	743.4	1423.02	50%	36%	54%	46%
4	Nominal	1052.9	458.6	545.8	1271.52	0%	0%	0%	0%
	Ingress II	440.8	606.8	405.5	852.66	58%	-32%	26%	33%
	Ingress III	496.4	327.8	428.6	733.18	53%	29%	21%	42%
	Ingress IV	517.6	456.9	486.4	844.48	51%	0%	11%	34%

Table 12: Overall Spike Moment Values - Egress

This chart displays the directional and resultant spike moment (in-lb) values for each of the four test subjects during each of their trials egressing the PFR.

Subject	Trial	Mx	My	Mz	R	Mx Diff	My Diff	Mz Diff	R Diff
1	Nominal	403.7	398.6	451.7	725.16	0%	0%	0%	0%
	Egress II	187.6	271.0	293.3	441.20	54%	32%	35%	39%
	Egress III	217.7	572.7	354.3	707.75	46%	-44%	22%	2%
	Egress IV	387.5	307.6	450.0	668.77	4%	23%	0%	8%
2	Nominal	353.9	352.2	575.3	761.77	0%	0%	0%	0%
	Egress II	574.9	737.6	644.6	1135.82	-62%	-109%	-12%	-49%
	Egress III	182.7	418.5	459.8	648.04	48%	-19%	20%	15%
	Egress IV	283.3	453.4	753.5	923.87	20%	-29%	-31%	-21%
3	Nominal	875.5	601.6	992.0	1453.39	0%	0%	0%	0%
	Egress II	767.9	770.9	833.6	1370.68	12%	-28%	16%	6%
	Egress III	777.1	1044.6	916.1	1591.99	11%	-74%	8%	-10%
	Egress IV	668.4	814.5	912.8	1394.00	24%	-35%	8%	4%
	Egress V	845.4	859.8	912.8	1512.33	3%	-43%	8%	-4%
4	Nominal	557.7	451.7	262.0	764.00	0%	0%	0%	0%
	Egress II	1074.9	545.8	420.4	1276.72	-93%	-21%	-60%	-67%
	Egress III	916.4	905.0	601.8	1421.63	-64%	-100%	-130%	-86%
	Egress IV	624.8	327.8	285.6	761.20	-12%	27%	-9%	0%

Appendix B: Additional Force and Moment Data

Table 13: Sustained Force and Moment Values Collected In Addition To Ingress/Egress Values

Subj.	Description	Fx	Fy	Fz	Mx	My	Mz
1	Standing in PFR (quiescent forces)	1.1	0.8	2.1	15.8	26.2	136.7
	Working on connector	2.3	2.6	3.3	93.9	74.9	106.4
2	Standing in PFR (quiescent forces)	1.4	2.2	1.1	107.2	55.0	52.9
3	Standing in PFR (quiescent forces)	0.5	2.4	3.0	55.7	94.9	

Table 14: Spike Force and Moment Values Collected In Addition to Ingress/Egress Values

Subj.	Description	Fx	Fy	Fz	Mx	My	Mz
1	Standing in PFR (quiescent forces)	3.7	3.7	6.2	55.7	94.9	217.4
	Working on connector	14.7	14.2	16.5	341.2	491.1	372.5
2	Standing in PFR (quiescent forces)	5.7	7.9	5.1	192.2	176.1	130.7
3	Standing in PFR (quiescent forces)	2.8	5.4	4.7	192.2	176.1	130.7